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ABSTRACT

This is a summary of observations of pulsars made with the *Compton Gamma-Ray Observatory* (CGRO) with emphasis given to milli-second pulsars. We present upper limits from the CGRO *Oriented Scintillation Spectrometer Experiment* (OSSE). We present a comparison between the gamma-ray luminosities and upper limits to the inferred magnetic field, spin-down rates, and dipole radiation. We explicitly demonstrate that several potential correlations between the gamma-ray luminosity and other properties of pulsars all have counter examples. The best predictor of a pulsar having a detectable gamma-ray emission appears to be the X-ray ($\sim 0.1 - 2.4$ keV) luminosities observed by the *Röntgen Satellite* (ROSAT). The likelihood of the gamma-ray detection of milli-second pulsars is not high. We base this on our observations and the ROSAT flux measurement of $\sim 4.5 \times 10^{-13}$ ergs cm^{-2} s^{-1} of the milli-second pulsar PSR J0437−47, plus the lack of a reported detection of 47 Tuc or PSR J0437−47 by CGRO.

INTRODUCTION

The gamma-ray study of pulsars is important not only because it provides insights into the physics of pulsars but because gamma rays are the dominant form of radiative energy loss for several isolated pulsars. Therefore, if we are going to understand the energetics of pulsars, it is necessary to observe them at gamma-ray energies. At the time of the presentation of this work we had not obtained upper limits to gamma-ray fluxes for pulsars from the EGRET team or the BATSE team and those of COMPTEL (Carramiñana *et al.* 1994) were comparable to those of OSSE. Therefore, we have restricted ourselves here to including only the OSSE upper limits and published results for other pulsars. The reader is referred to Thompson *et al.* (1994) and Fierro *et al.* (1994) for the latest EGRET upper limit results. Thompson *et al.* and Fierro *et al.* reach conclusions similar to those we reach here.

OBSERVATIONS AND RESULTS

For over three years the *Compton Gamma-Ray Observatory* Oriented Scintillation Spectrometer Experiment (CGRO/OSSE) has collected data from many known radio and X-ray pulsars. Five pulsars (Crab, Vela, PSR B1706−44, PSR B1055−52, and Geminga) have been detected by the CGRO Energetic Gamma-Ray Experiment Telescope (EGRET) and three (Crab, Vela, and PSR B1509−58) have been detected by OSSE (cf. Ulmer 1994). We present OSSE 2σ upper limits on fifteen additional pulsars. The details of the analysis and observations will be presented elsewhere (Schroeder *et al.* 1994). We therefore only briefly describe the OSSE observations and analysis. For detailed descriptions of the CGRO experiments see: Wilson *et al.* (1992, BATSE); Schoenfelder *et al.* (1993, COMPTEL); Thompson *et al.* (1993, EGRET); and Johnson *et al.* (1993, OSSE).

Due to telemetry constraints OSSE cannot analyze pulsars over the full extent of the OSSE energy range ($\sim 0.05 - 10$ MeV). The energy ranges were therefore set to cover that portion of the spectrum where we judged OSSE would have the best chance of detecting a given pulsar. Further, we adjusted the band width so that the telemetry could accommodate (with a dead time loss of $\leq 20\%$) the detector background counting rate within that energy range. Except in the case of PSR B1957+20, all the other measurements were within the ~ 0.05 to 0.2 MeV energy range.

OSSE has spent a significant amount of time observing fifteen known pulsars, nearly all of which were expected to be good candidates for detection in low-energy gamma rays because of their detection in high-energy gamma rays by EGRET or their relatively high $\dot{\mathrm{E}}/\mathrm{d}^2$ ratios ($\dot{\mathrm{E}}/\mathrm{d}^2 > 10^{34}$ ergs s^{-1} kpc^{-2}) , where $\dot{E}$ denotes the inferred rotational energy loss and d is the distance to the pulsar (cf. Taylor, Manchester, & Lyne 1993). Data taken during the observation of each pulsar were folded using the appropriate radio ephemeris (Taylor *et al.* 1992), except in the case of Geminga where the gamma-ray ephemeris (Mayer-Hasselwander *et al.* 1994) was used.

We searched the folded data for evidence of a pulsed signal by using a χ^2 test of the fit to a constant intensity. We also visually inspected plots of the data. Further, we fitted each data set with a circular normal (von Mises) function with a full width half maximum in phase of both 0.5 and 0.3. We found no evidence for a statistically significant signal from any of the pulsars in our sample. We therefore computed the upper limits using the prescription of Ulmer *et al.* (1991) which scales with the square root of the detector background counts and total live time, and we have assumed a pulse width of 0.5 in phase. In Table I we present the 2σ upper limits to the phase averaged flux.

We converted these flux limits into upper limits to the gamma-ray luminosities by assuming a spectrum $\propto \mathrm{E}^{-2}$ for all the pulsars except Geminga and PSR B1706−44, for which the observed EGRET spectra were used. The OSSE upper limit for PSR B1706−44 was found to lie above the spectral fit found by Thompson *et al.* (1992), so their fit was used to calculate the pulsar's luminosity. The luminosity for Geminga was estimated by assuming a spectral break (at 5.3 MeV, the spectral number index above the break = 1.55 and 0.6 below) between the observed EGRET spectrum (Mayer-Hasselwander *et al.* 1994) and the OSSE upper limit. For PSR B1706−44, we assumed the spectral index within the uncertainties of the EGRET measurement that produced a flux that extrapolated to the ROSAT value. For PSR B1055−52 the spectrum is so flat and the spectral index so uncertain, that we have taken all the flux as having

TABLE I Gamma-Ray Luminosity Upper Limits

Pulsar B	$P^{(a)}$	log $\dot{P}^{(b)}$	B$^{(c)}$	d$^{(d)}$	Energies$^{(e)}$	$F_\gamma^{(f)}$	$L_\gamma^{(g)}$
0114+58∗	0.10144	-14.23	7.73E11	2.12	46 - 292	1.85E-7	1.64E34
0950+08	0.25307	-15.64	2.41E11	0.12†	58 - 208	3.59E-7	9.15E31
1046−58	0.12365	-13.02	3.44E12	2.98	47 - 161	4.54E-7	4.48E34
1702−19	0.29899	-14.38	1.12E12	1.19	38 - 85	2.51E-7	1.68E33
1706−44	0.10244	-13.03	3.09E12	1.82	31 - 87	3.20E-6	2.51E35
1800−21	0.13358	-12.87	4.24E12	3.94	77 - 171	6.60E-7	1.98E35
1821−24	0.00305	-17.81	2.17E09	5.50†	70 - 161	1.06E-6	5.30E35
1822−09∗	0.76896	-13.28	6.35E12	1.03	64 - 155	6.78E-7	1.05E34
1855+09∗	0.00536	-19.70	3.27E08	1.00†	35 - 59	4.26E-6	1.29E34
1929+10	0.22562	-14.94	5.10E11	0.17	30 - 173	1.83E-7	4.03E31
1937+21	0.00156	-19.00	3.95E08	3.58	77 - 161	2.66E-7	6.20E34
1951+32	0.03953	-14.23	4.82E11	2.50†	74 - 402	9.62E-8	2.62E34
1957+20∗	0.00161	-19.80	1.60E08	1.53	326 - 616	4.53E-7	3.13E35
2334+61∗	0.49524	-12.72	9.71E12	2.46	76 - 174	7.59E-7	8.91E34
Geminga	0.23700	-13.96	1.61E12	0.15†	76 - 566	1.61E-8	2.65E33

Notes:

∗ The upper limits for these exceed the estimated total rotational energy loss.
† Due to the availability of additional data, means other than the Taylor & Cordes (1993) dispersion measure model were used to determine the distances.
a. Pulsar period in units of s.
b. Log of the time derivative of the period.
c. Magnetic field strength in gauss.
d. Distance in kpc.
e. Energy range of the OSSE observation in keV.
f. Gamma-ray flux upper limit for the given energy range in photons cm^{-2} s^{-1} keV^{-1}.
g. Gamma-ray luminosity upper limit (0.1 MeV – 1 GeV) in ergs s^{-1}.

an average value of 2×10^{-10} photons cm^{-2} s^{-1} over the 100 MeV to 1 GeV range only, and an average photon energy of 500 MeV. For our assumed beaming factor this yields a value of the gamma-ray radiation efficiency of about 0.4. We have marked the pulsars in Table I which we have not plotted at their observed upper limits as these are higher than the total estimated rotational energy loss. Instead, we used 90% of the rotational energy loss as a conservative upper limit. Distances to the pulsars were taken from the Taylor *et al.* (1993) catalog. These distances were primarily based on a model of Taylor & Cordes (1993) which converts dispersion measure to distance. For the Geminga pulsar, which has not been detected in the radio, we have assumed the distance to be 0.15 kpc [see Thompson *et al.* (1994), and Halperin & Ruderman (1993), for discussions of the distance estimate]. Finally, we assumed the width of the pulsar beam perpendicular to the pulse plane passing through the Earth to be 90° (e.g., the flux limits were converted to luminosity limits by multiplying by $2\pi d^2$).

These results are summarized in Tables II (CGRO detections) and III [selected ROSAT detections from Ögelman (1994)]. Since the emphasis of this conference is on milli-second pulsars and since 47 Tuc may have hundreds or thousands of pulsars (see Barret *et al.* 1993, and references therein), we have also included an upper limit to 47 Tuc in the comparisons below. The 2σ upper limit to the steady flux in the $\sim$ 55 to 150 keV energy range corresponds to about 5×10^{-5} photons cm^{-2} s^{-1} or about 0.4 Crab pulsars (Ulmer 1994, and references therein). For the sake of deriving a concrete value we have assumed that 47 Tuc is at a distance of 5 kpc [Taylor *et al.* (1993) estimate 4.5 kpc, and Barret *et al.* (1993) estimate 4.1 kpc for the distance] and that 47 Tuc contains

TABLE II Properties of Previously Detected CGRO Pulsars

Name	$P^{(a)}$	log $\dot{P}^{(b)}$	B$^{(c)}$	d$^{(d)}$	$F_\gamma^{(e)}$	$L_\gamma^{(f)}$
Crab	0.03333	-12.38	3.73E12	2†	8.1E-9	1.8E36
Vela	0.08928	-12.91	3.31E12	0.5†	9.4E-9	1.4E35
PSR B1055−52	0.19711	-14.23	1.08E12	1.53	1.4E-10	1.9E34
PSR B1509−58	0.15023	-11.81	1.53E13	4.4†	3.4E-10	3.7E35
PSR B1706−44	0.10244	-13.03	3.09E12	1.82	2.1E-9	4.1E35
Geminga	0.23700	-13.96	1.61E12	0.15	1.9E-9	2.6E33

Notes:
† Due to the availability of additional data, means other than the Taylor & Cordes (1993) dispersion measure model were used to determine the distances.
a. Pulsar period in units of s.
b. Log of the time derivative of the period.
c. Magnetic field strength in gauss.
d. Distance in kpc.
e. Gamma-ray flux, 0.1 MeV – 1 GeV, except for PSR B1055−52 (see text), in units of ergs cm^{-2} s^{-1}.
f. Gamma-ray luminosity in units of ergs s^{-1}.

TABLE III X-Ray Properties of Selected Pulsars

Name	$F_x^{(a)}$	$L_x^{(b)}$
Crab	2.1E-9	5.0E35
Vela	1.7E-12	2.5E31
PSR B1055−52	3.3E-13	4.6E31
PSR B1509−58	9.5E-12	1.1E34
PSR B1706−44	4.3E-13	8.5E31
Geminga	3.3E-13	4.5E29
PSR B1951+32	1.3E-12	5.0E32
PSR B0950+08	8.4E-14	7.2E28
PSR B1929+10	8.4E-14	1.4E29
PSR J0437−47	3.7E-13	5.0E29

Notes:
a. X-ray flux, 0.1 keV – 2.4 keV in units of ergs cm^{-2} s^{-1}.
b. X-ray luminosity in units of ergs s^{-1}.

1000 milli-second pulsars so that, *per pulsar*, the upper limit we have derived corresponds to a flux limit of $\sim 4 \times 10^{-4}$ Crab pulsars and a corresponding luminosity of $\sim 2.5 \times 10^{-3}$ Crab pulsars. The upper limit to the flux from 47

Tuc is about a factor of 7 lower than that reported by Barret *et al.* in the same energy range.

DISCUSSION

In Figure I we show an artist's conception of a pulsar.

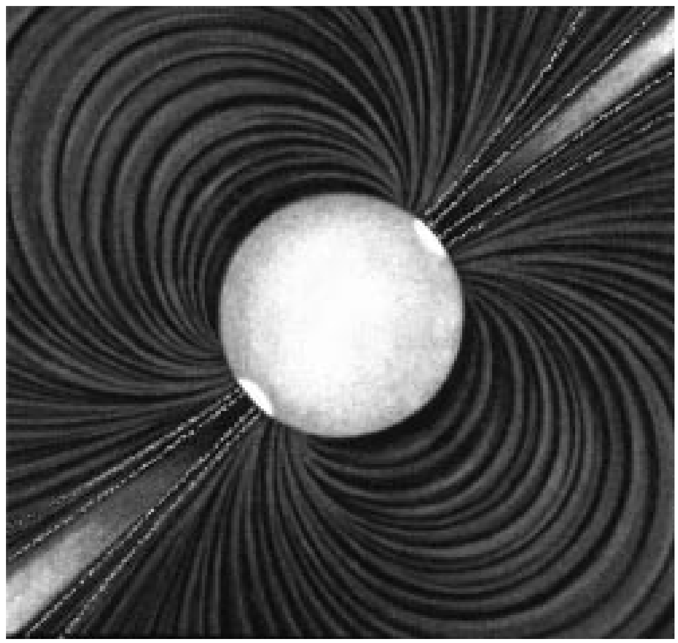

FIGURE I An artist's conception of a pulsar

We use this figure as a framework for the following model: while particles are accelerated out to produce beams of non-thermal radiation in the form of gamma rays, the particles are also accelerated down onto the neutron star polar cap surface. The particles heat the polar cap regions and we suggest that the number of particles accelerated upward is nearly equal to the number accelerated downward such that heating of the polar caps is proportional to the gamma-ray emission that is produced. Therefore, in this scenario, even if the non-thermal spectrum does not extend to soft X-ray energies we expect a correlation between the X-ray luminosity (from thermal emission) and the gamma-ray luminosity. This is indeed found and is shown in Figure II.

We see that this predictor is not perfect: PSR B1509−58 is easily detectable by ROSAT and not by EGRET; and, the Vela pulsar is easily detectable by EGRET but is only detected with difficulty by ROSAT. For PSR J0437−47 we have used the lack of a report of a discovery by the EGRET team to estimate that the flux must be less than or equal to that of PSR B1055−52. OSSE has not yet observed this object.

As can be seen in Figure III, detected gamma-ray pulsars seem to suggest

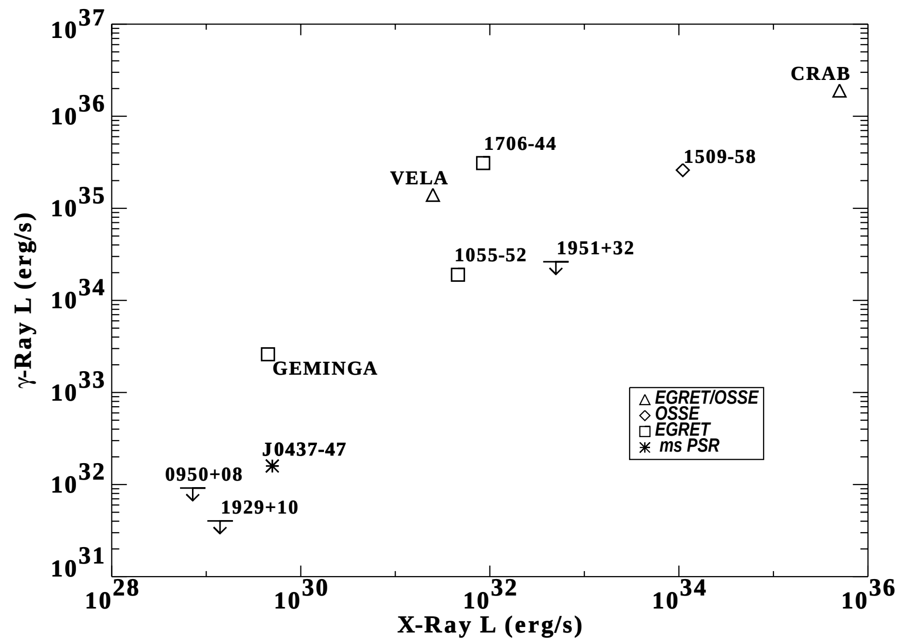

FIGURE II The gamma-ray luminosity versus X-ray luminosity.

that gamma-ray production efficiency increases with decreasing rotational energy loss. The upper limits for some pulsars lie below the trend for detections, however. The trend seen with the detected pulsars is probably a selection effect (i.e., if the overall energy loss is low, then the efficiency must be high for the pulsar to be detected).

We next compare our upper limits and detections against some other characteristics of pulsars which might be expected to play a significant role in the origin of the gamma-ray emissions: inferred magnetic field and inferred dipole radiation. Figures IV and V show that although, on average, the gamma-ray luminosity of pulsars seems to depend on the pulsar magnetic field or dipole radiation loss, there are counter examples.

For brevity we will not show similar comparisons of gamma-ray luminosities (and upper limits) to the pulsar frequency, or the gamma-ray efficiency to the characteristic age. But we remark that, as with those we have presented here, there are upper limits that provide counter examples to any apparent correlation between gamma-ray luminosity and these other quantities (see also Thompson *et al.* 1994; and Fierro *et al.* 1994).

We next turn to a consideration of future prospects in terms of current upper limits and CGRO's sensitivity. For this we have examined the data in two ways: first we use a plot of the flux versus $\dot{E}/d^2$ in order to rank pulsars in $\dot{E}/d^2$. This allows us to compare upper limits of milli-second pulsars to detections and other upper limits.

In Figure VI we see that optimistically we would have expected to detect all pulsars with a higher rank (to the right) than that of PSR B1055−52. The

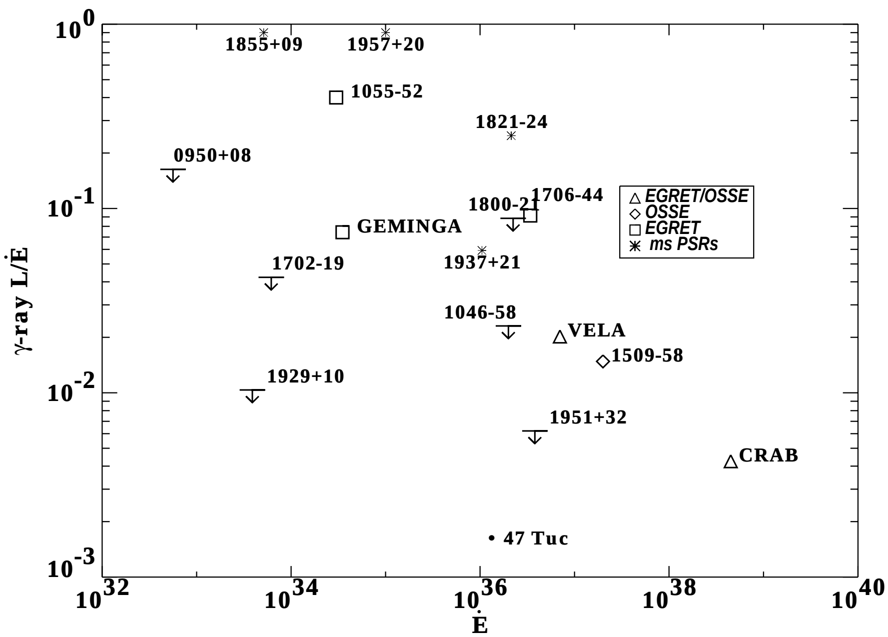

FIGURE III The gamma-ray production efficiency versus rate of energy loss.

efficiency of converting rotational energy loss to gamma-ray flux is an important characteristic as well (the diagonal lines in Figure VI represent the locus of points for 100% and 1% efficiencies for converting rotational energy into gamma-rays), but even when the efficiency is taken into account we would have expected to detect 47 Tuc and PSR B1951+32. For the case of 47 Tuc we have assumed a rotational energy loss per pulsar comparable to those of milli-second pulsars such as PSR B1957+20 and PSR B1822−09, e.g 2.5×10^{34} ergs s^{-1} along with the previously noted assumptions of $d = 5$ kpc and the existence of 1000 pulsars in the cluster. Even reducing the average energy loss per milli-second pulsar in 47 Tuc by a factor of 10 is not enough to move 47 Tuc to the left of PSR B1055−52, nor would reducing the assumed number of pulsars in 47 Tuc by a factor of 10 remove the prediction that 47 Tuc should have been detected if milli-second pulsars were on the average gamma-ray emitters similar to PSR B1055−52.

CONCLUDING REMARKS

We have not been able to find a set of pulsar characteristics that we can use as a reliable predictor of when a pulsar will be detectable in the hard X-ray/gamma-ray ($\gtrsim$ 50 keV) region. In terms of being able to predict detectability or non-detectability in the gamma-ray energy range: if the X-ray flux is high enough, then a pulsar will be detectable as a gamma-ray source; and if a pulsar is a milli-second (period $\lesssim$ 10 ms) pulsar, then it is likely to be undetectable as a gamma-ray source. We suggest that possible reasons we have failed to detect

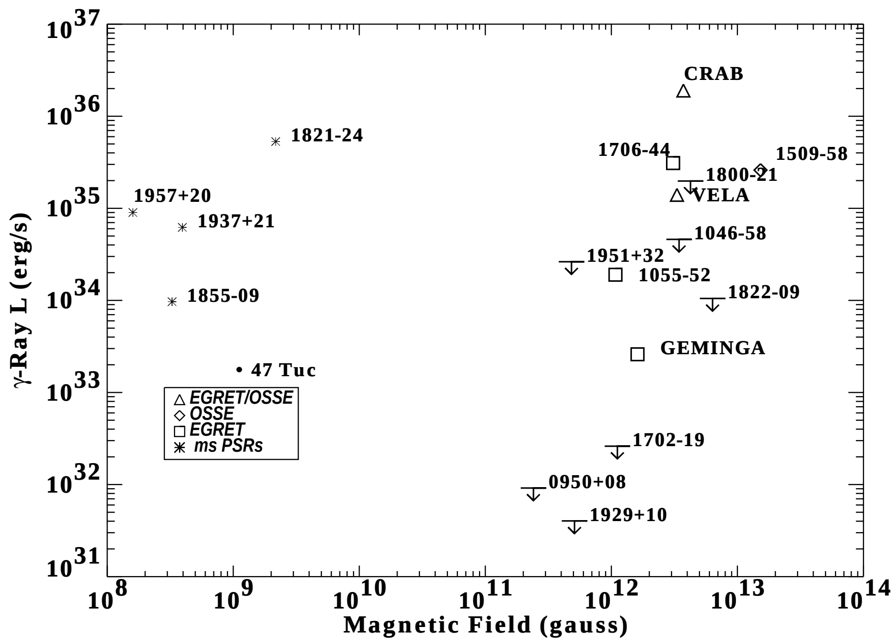

FIGURE IV The gamma-ray luminosity versus magnetic field strength.

these milli-second pulsars are: they all have low magnetic fields; and/or, if they did "turn on" as gamma-ray emitters they would radiate their rotational energy away so efficiently that they would not last long enough to be detected as milli-second pulsars. Searches for young rapidly rotating pulsars in systems such as SN1987A may eventually shed more light on the ability of milli-second pulsars to radiate in the hard X-ray/gamma-ray region.

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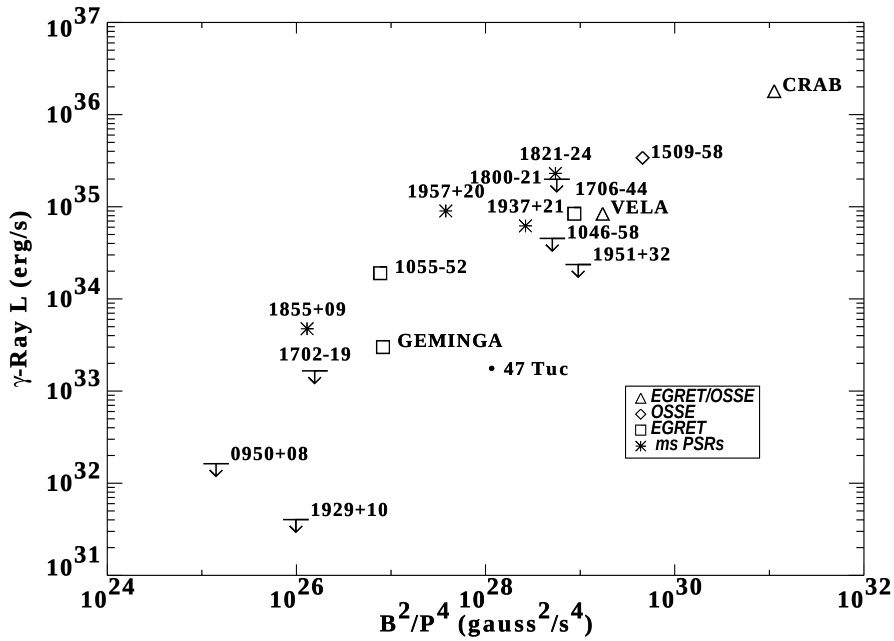

FIGURE V The gamma-ray luminosity versus B^2P^{-4}.

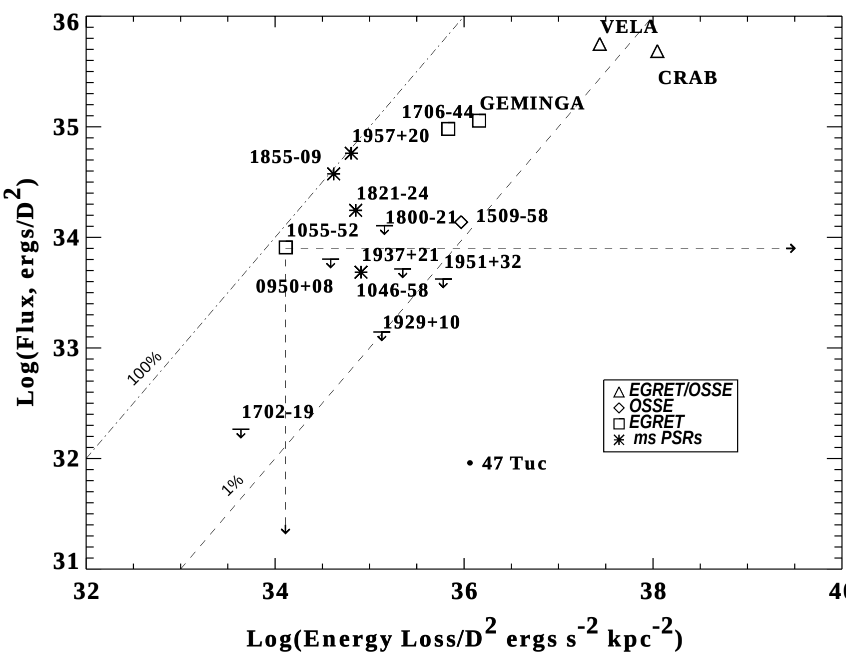

FIGURE VI The measured gamma-ray flux versus the expected total flux

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